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Systems Definition Space Based Power Conversion Systems

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Final Report
Executive Summary

BOEING

FINAL REPORT

EXECUTIVE SUMMARY (DPD ITEM MA-04)

SYSTEMS DEFINITION SPACE-BASED POWER CONVERSION SYSTEMS

Submitted to:
The National Aeronautics and Space Administration
George C. Marshall Space Flight Center

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NAS 8-31628

The Boeing Aerospace Company

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1.0 INTRODUCTION

This study investigated potential space-located systems for the generation of electrical power for use on Earth. These systems were of three basic types:

- (1) Systems producing electrical power from solar energy;
- (2) Systems producing electrical power from nuclear reactors;
- (3) Systems for augmenting ground-based solar power plants by orbital sunlight reflectors.

Systems (1) and (2) would utilize a microwave beam system to transmit their output to Earth.

Configurations implementing these concepts were developed through an optimization process intended to yield the lowest cost for each. A complete program was developed for each concept, identifying required production rates, quantities of launches, required facilities, etc. Each program was costed in order to provide the electric power cost appropriate to each concept.

Mr. Walter Whitacre was contracting officer's representative at Marshall Space Flight Center. At Boeing, the study effort was directed by Daniel Gregory. Subcontractors were: the Garrett Corporation (thermal engines), directed by Mr. Anthony Pietsch, and the Thermo Electron Corporation (thermionics) directed by Dr. Peter Oettinger. Dr. J. Richard Williams of the Georgia Institute of Technology was the consultant on space-based nuclear reactors.

Studies which were underway during some portion of the study and which contributed to the data base are:

1. NAS8-31308 (MSFC), "Space-Based Solar Power Conversion and Delivery Systems Study" Econ Incorporated,
2. NAS9-14323 (JSC), "Future Space Transportation Systems Analysis Study", Boeing Aerospace Company.
3. NAS3-17835 (LeRC), "Microwave Power Transmission System Studies" Raytheon/Grumman.
4. NAS9-14710 (MSFC), "Systems Concepts for STS-Derived Heavy Lift Launch Vehicle Study" Boeing/Grumman.
5. Contract NAS8-31444 (MSFC), "Payload Utilization of SEPS" Boeing/GE.
6. Contract E-(04-3)-1111 (ERDA) "Central Receiver Solar Thermal Power System". Boeing Engineering and Construction.

2.0 THE SOLAR POWER SATELLITE CONCEPT

2.1 POWER SATELLITES AND GROUND RECEIVERS

Figure 2-1 may be used to understand the basic principle of the Satellite Power Station (SPS). A power generating system produces electric power which is converted into a narrow (total divergence angle of approximately 1/100 degree) microwave beam by the microwave transmitter. These systems are located in equatorial geosynchronous orbit and thus remain in line-of-sight of their associated microwave power receiving stations on the ground. At these stations the microwave power is converted into a form of electricity suitable for insertion into the local power network. The energy source for the SPS would be sunlight, or alternatively, nuclear reactors.

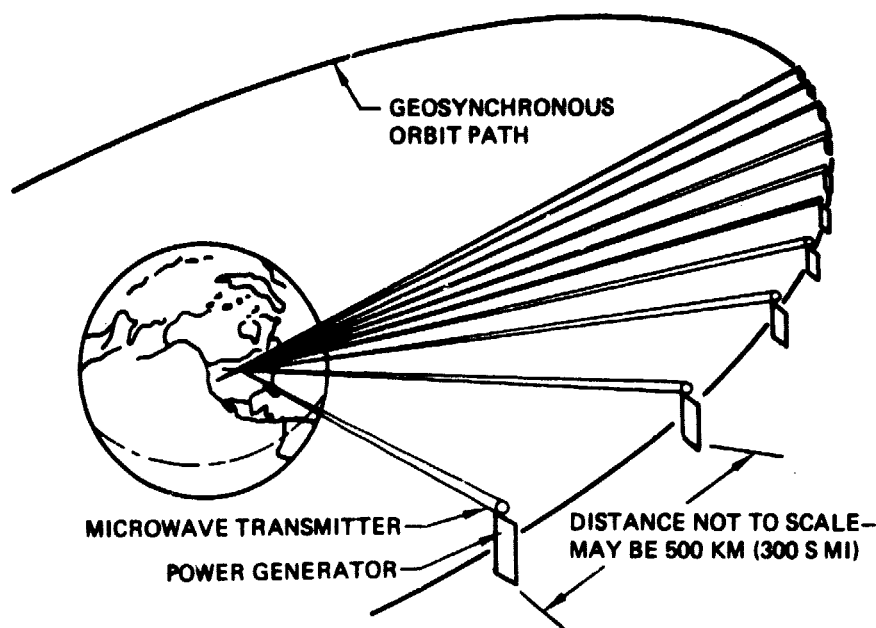


Figure 2-1. Satellite Power Stations

The receiving stations for the SPS consist of a large number ($\approx 10^9$) of small receiving antennas integrated in an oval array. Rectification of the received energy to direct current is accomplished by circuit elements which are integral to the antennas. Figure 2-2 shows such an array.

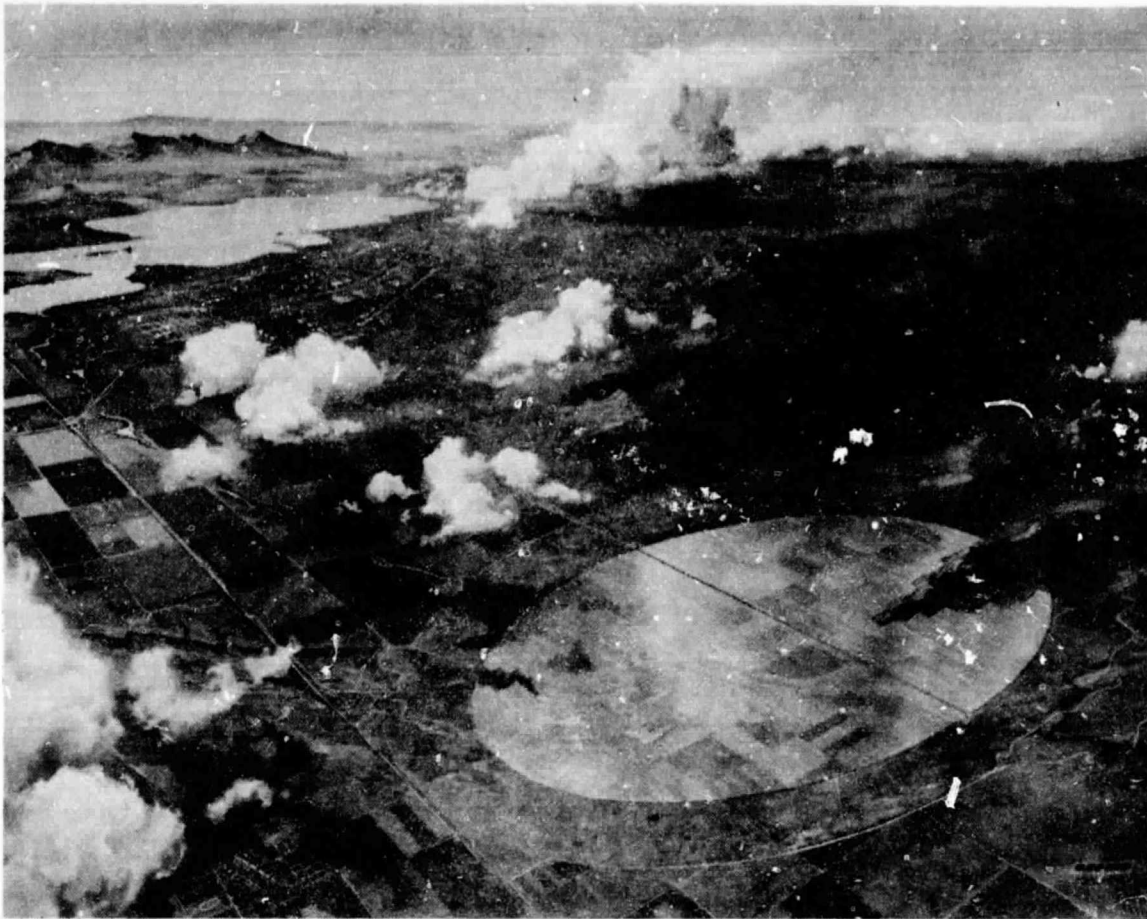


Figure 2-2. Receiving Antenna

Since the antenna may block most of the microwave energy but would be nearly transparent to sunlight, it is possible that agriculture could be accomplished beneath it. Surrounding the antenna is a buffer zone to contain those microwave "side-lobes" which are more energetic than the continuous exposure standard (assumed to be more than 10 times more stringent than the current standard). These antennas could be placed relatively near demand points (Note the city in the background of Figure 2-2).

Figure 2-3 shows, as an example, one of the concepts studied; a solar Brayton SPS. Four power generator modules feed the circular microwave transmitter. Each power module consists of a reflector which concentrates solar energy into a cavity absorber at the focal point. The resultant high temperatures are used to energize turbo-machines which turn electrical generators which power the transmitter.

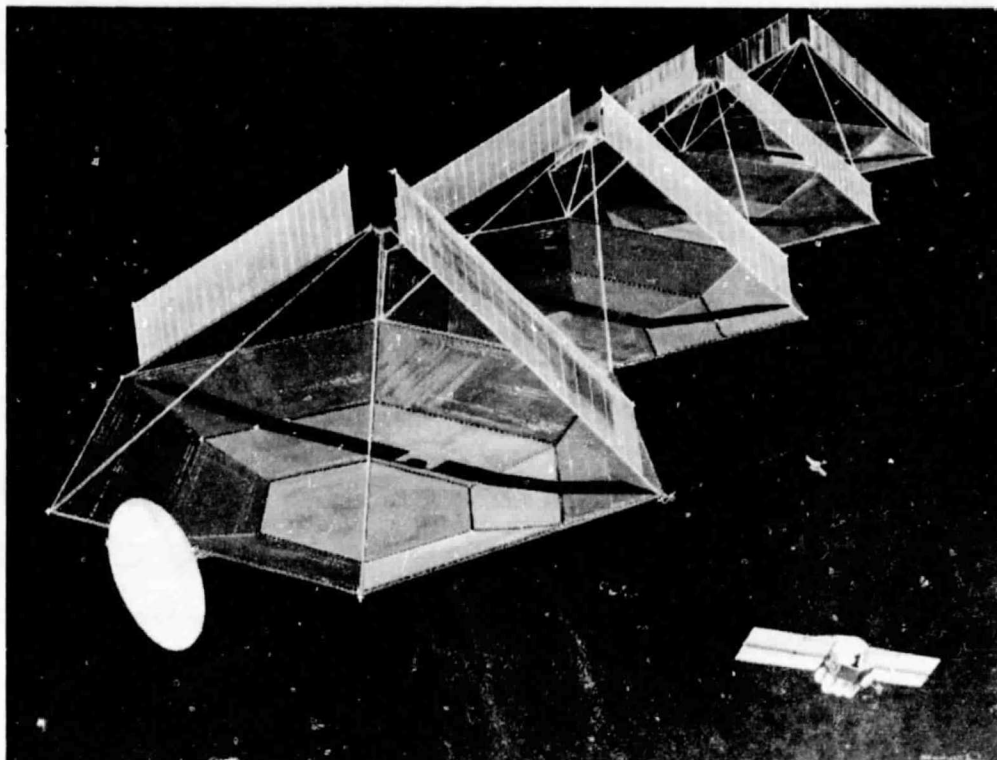


Figure 2-3. Solar Turbomachine Power Satellite Option

In this study the technical and economic practicality of these systems was investigated. While these systems produce large quantities of power (e.g., 10,000,000 kilowatts per satellite), the forecasted demands of the United States alone are sufficient to require a significant number of satellites. In the program baselined in this study, 60 satellites are made operational by the year 2016.

2.2 AUXILIARY SYSTEMS

The criterion for optimization of these systems was minimum cost per kilowatt hour of energy produced (while maintaining set standards on factors such as environmental impact). To achieve low cost per kWhr, all significant elements of the program must also be appropriately low in cost. This includes not only the power generation and transmission systems, but also the systems used for space transportation and space assembly. These auxiliary systems were of necessity considered in this study although their investigation was not a primary goal. An example of an auxiliary system is the heavy lift launch vehicle ("space freighter") used to transfer SPS material to low orbit. It is shown in Figure 2-4 during the landing phase; a portion of the ascent propulsion system is used to affect a soft landing in water. Thus the vehicle is available for reuse, contributing to the required low operational cost.

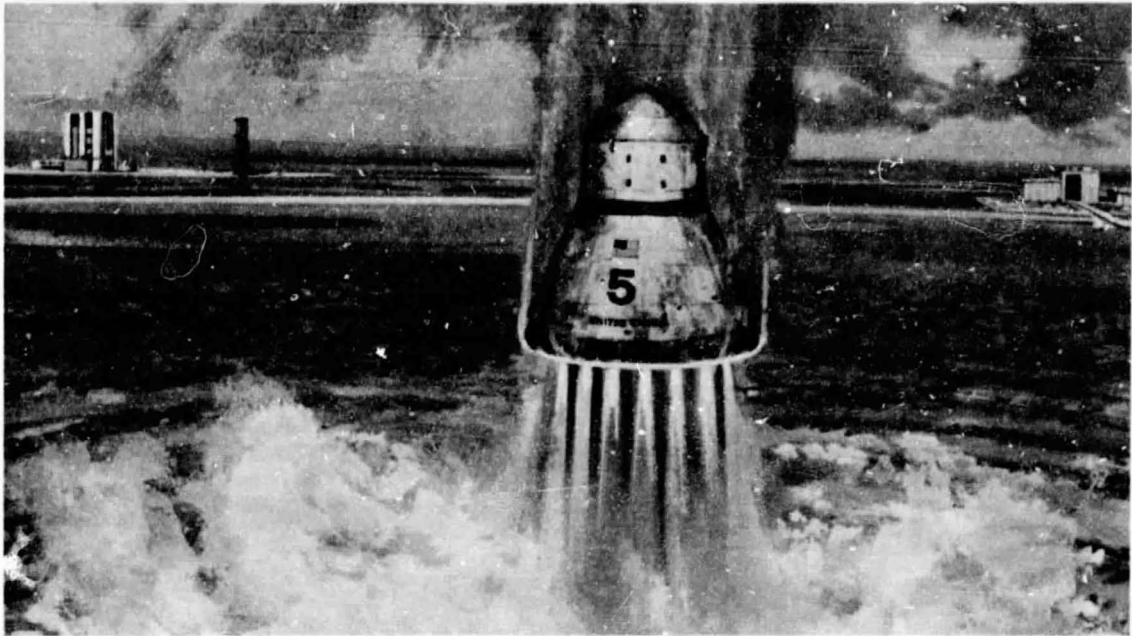


Figure 2-4. "Space Freighter" Lands

Another significant auxiliary system is the orbital construction facility required to provide the necessary production rate for satellite power stations. A concept for such a station is shown in Figure 2-5.

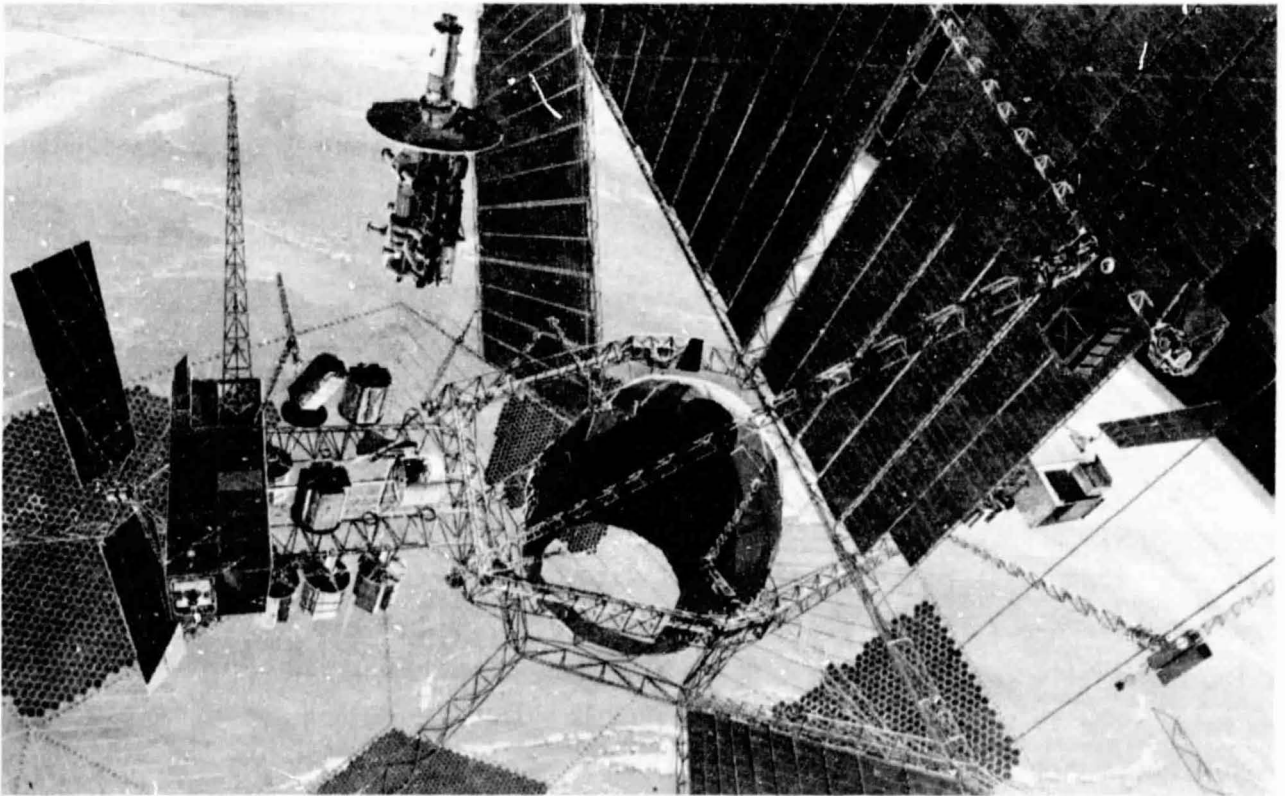


Figure 2-5. Orbital Construction Facility

3.0 ALTERNATIVE POWER GENERATION APPROACHES

3.1 CONCEPTS INVESTIGATED

The alternative satellite power systems shown in Table 3-1 were investigated:

Table 3-1. Alternative Power Systems

Concept	Energy Source	Energy Converter
1	Solar	Direct Radiation Cooled Thermionic
2	Solar	Liquid Cooled Thermionic
3	Solar	Closed Brayton Cycle
4	Solar	Thermionic/Brayton Cascade
5	Solar	Silicon Photovoltaic
6	Solar	Gallium Arsenide Photovoltaic
7	Nuclear	Thermionic
8	Nuclear	Closed Brayton Cycle
9	Solar (Light Reflector)	Ground-Based Solar Power Plants

The last concept does not generate power in space; a mirror system in geostationary orbit would reflect sunlight to an area on Earth, potentially allowing night operation of ground solar power plants.

By the end of the initial phase of this study, it had become evident that further investigation of concepts 2, 4, 7 and 9 was inappropriate for the reasons given in Table 3-2.

Table 3-2. Evaluation of De-emphasized Systems

Concept	Reason for De-emphasis
2	More massive than Concept 1
4	No advantage over Concept 3
7	Extremely massive/not technically feasible
9	Extreme environmental impact

Background data for Table 3-2 may be found in the companion volume "Detailed Technical Report".

3.2 THEORIES OF OPERATION

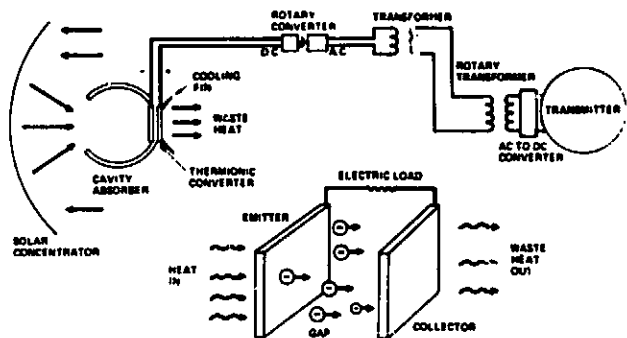
Figure 3.1 provides a brief explanation of the basic principles involved in each concept selected for additional investigation.

CONCEPT 1 SOLAR THERMIONIC DIRECT RADIATION COOLED

In a thermionic diode, electrons are produced at the emitter (cathode) due to its elevated temperature, and travel to the lower temperature collector (anode). The circuit is completed through the load. Several processes within the emitter-collector gap tend to reduce the efficiency of power generation from the applied thermal energy. For example, the electrons in the gap tend to repel those being produced at the emitter.

The diodes are mounted in the wall of the solar cavity absorber; the emitters are heated by the concentrated solar energy. By allowing the collectors to dissipate waste heat to space the temperature differential required for operation is produced. Fins are added to the collectors to improve cooling.

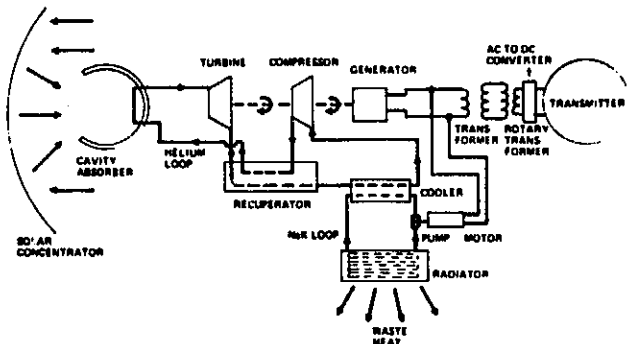
Individual diodes have outputs of approximately 0.8 volts, and it is not practical (due to insulation breakdown) to use series strings to produce the 20,000 volts required by the transmitter. Therefore, rotary converters are used to step up the voltage.



CONCEPT 3 SOLAR CLOSED BRAYTON CYCLE

The Brayton cycle turbomachine provides a rotating shaft output which drives the generators. Thermal energy is added to the helium working fluid in heat exchanger tubing located within the cavity absorber. The hot gas is expanded through the turbine, providing power to turn both the compressor and generator. The recuperator exchanges energy across the loop to increase the system efficiency. Waste heat is rejected through a gas-to-liquid heat exchanger to a liquid metal cooling loop; the liquid metal pumps use power drawn from the generators.

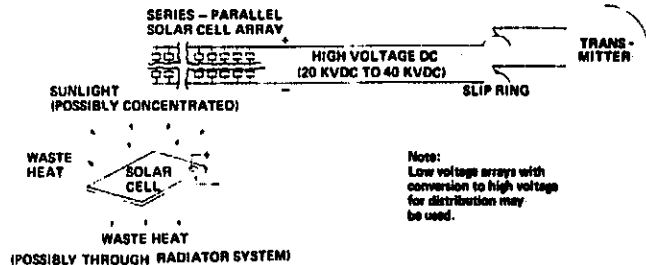
The 10,000 volt ac output of the generators is stepped-up to 382,000 volts in transformers; this high voltage facilitates on-board distribution. Step-down occurs in the rotary transformers.



CONCEPTS 5 & 6 SOLAR PHOTOVOLTAIC

A photovoltaic, or solar, cell directly converts solar energy to electric power. Performance may be augmented, within certain limits, by concentrating solar energy upon the cell and/or by providing cooling.

Series strings of cells may be used to build to the 20,000 vdc (or 40,000 vdc), nominal, required for the microwave transmitter. Lower voltage arrays may be required if low orbit operation is required (such as for self-powered transfer) due to plasma phenomena.



CONCEPT 8 NUCLEAR CLOSED BRAYTON CYCLE

The energy source in this system is nuclear; a UF_6 gaseous breeder reactor is used.

A "breeder" secondary salt flow is continuously passed through a fuel process system. This system removes the wastes. The fuel process system introduces fertile fuel and removes bred fuel.

The Brayton cycle turbomachine provides a rotating shaft output which drives the generators. Hot helium is expanded through the gas turbine, providing power to drive both the compressors and generators. The recuperator exchanges energy across the loop to increase efficiency. Waste heat is rejected through a gas-to-liquid heat exchanger to a liquid metal cooling loop; the liquid metal pumps use power drawn from the generators.

The 10,000 volt ac output of the generators is stepped-up to 382,000 volts in transformers; this high voltage facilitates on-board distribution. Step-down occurs in the rotary transformers.

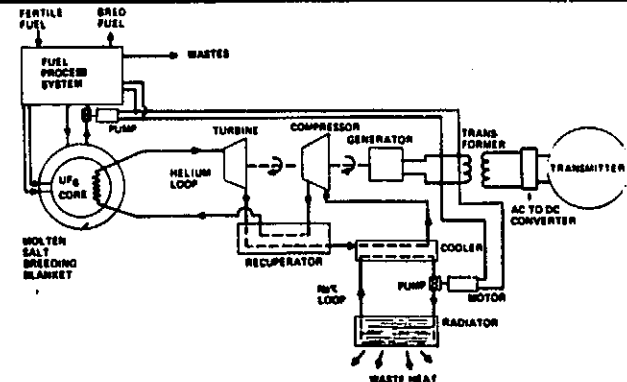


Figure 3-1. Principles of Operation

3.3 CONFIGURATION DEVELOPMENT

Details of the configuration development process are given in the companion volume "Detailed Technical Report"; a summary is given below.

3.3.1 Subsystem Analysis (Examples)

Primary subsystems were separately analyzed. These subsystems were:

- Solar Concentrators
- Cavity Absorbers
- Solar Cells
- Turbomachines
- Nuclear Reactors
- Power Distribution
- Radiators
- Structure

Some subsystems are common to more than one power satellite concept; for example, radiators and turbomachines are used in both the nuclear Brayton and solar Brayton concepts.

Each subsystem was parametrically described to permit evaluation over a wide range of input parameters. For example, a radiator system has the following primary input parameters: power to be radiated, inlet temperature and outlet temperature. A computerized processing of the parametric model was used to find that radiator configuration which has minimum mass yet meets the primary input parameters. Figure 3.2 shows the results of this optimization process for radiators over a wide inlet temperature range for a power dissipated of 8 GWT.

In one case subsystem configuration optimization was more appropriately based on cost than on mass. This case was the solar cell subsystem, including any provisions for concentrating sunlight on the cell or for cooling the cells. As more and more solar concentration is used, less and less cell area (hence cost) is required for a given power output up to the point where increasing cell temperature has too high an impact on cell efficiency. Cooling the cells allows more solar concentration for a given cell temperature. The computerized optimization process indicated minimum on-orbit busbar costs if a solar concentration ratio of 4.3 was used for silicon cells; a ratio of 7.5 was appropriate for gallium arsenide heterojunction cells.

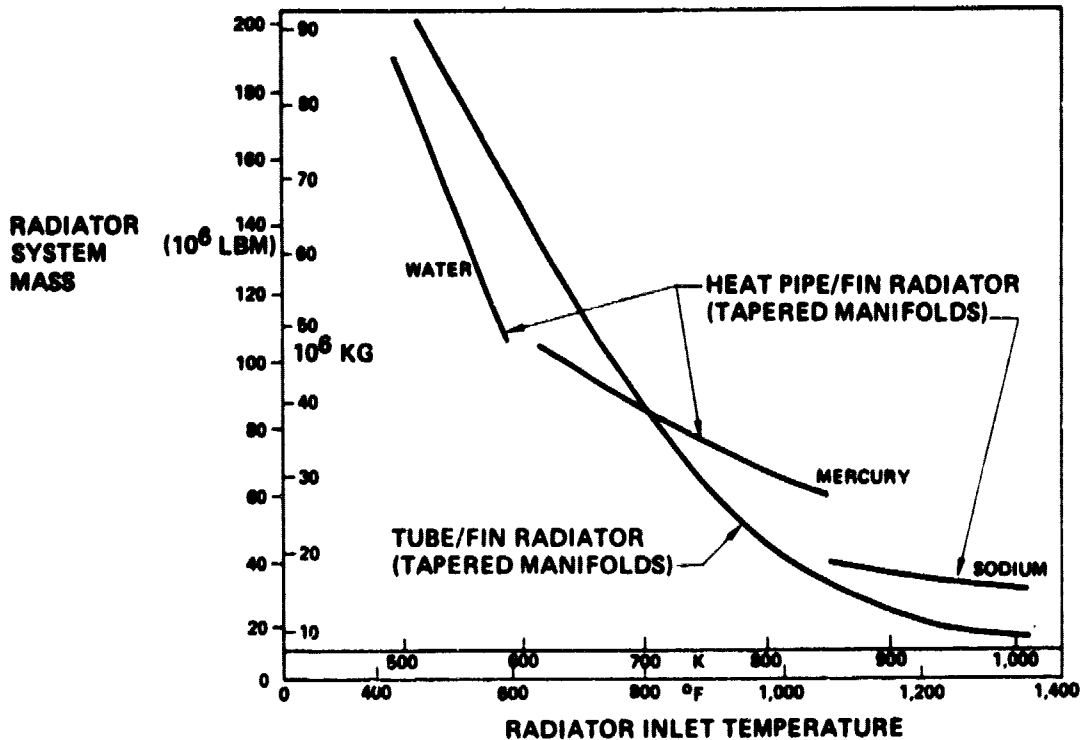


Figure 3-2. Radiator Mass as a Function of Inlet Temperature

Another significant optimization related to solar cells was the determination of ideal cover glass thickness. The required operational life of the cells is equal to that baselined for the entire satellite: 30 years. In 30 years the cells are exposed to significant radiation effects, tending to cause relatively high degradation fractions. Both the normal flux of electrons and the protons associated with solar flares must be taken into account. Thick cover glass provides good protection, but is heavy, adversely impacting boost cost. Any cooling fins attached behind the cells also provide radiation protection; hence the cover glass optimization must be integrated with the solar concentration/cooling optimization.

Table 3-3 summarizes significant parameters from these optimizations.

Table 3-3. Solar Cell Subsystem Parameters

Cell Type	Concentration Ratio	Cover Thickness		Cooling Fin Thickness		Cell Temperature		Initial Cell Efficiency %	Cell Efficiency After 30 Years, %
		μM	Mils	μM	Mils	K	$^{\circ}\text{F}$		
Silicon	4.3	200	7.9	110	4.3	367	201	11.23	7.59
Gallium Arsenide	7.5	100	3.9	29	1.1	427	309	12.81	11.09

4.0 SATELLITE CONFIGURATIONS

4.1 CONFIGURATION OPTIMIZATION

Preliminary configuration concepts were used to define the primary relationships between subsystems in a complete satellite system. The subsystems were themselves defined by their primary parameters; refer back to Figure 3-1 to see how inlet temperature influences radiator mass. In a Brayton system high engine efficiency tends to yield low total mass, yet high engine efficiency requires a low radiator temperature, tending towards a massive radiator. Machine processing of the system model provided the total set of subsystem parameters for a minimum mass total system. The program used was ISAIH (Integrated Sensitivity and Interactions Analysis, Heuristic). As previously explained, solar subsystem optimization was done on the basis of cost. All SPS types shown have a 10 GW ground output.

4.2 PHOTOVOLTAIC SATELLITE CONFIGURATIONS

Figure 4-1 shows the general arrangement of the silicon and gallium arsenide solar cell satellite configurations.

SILICON

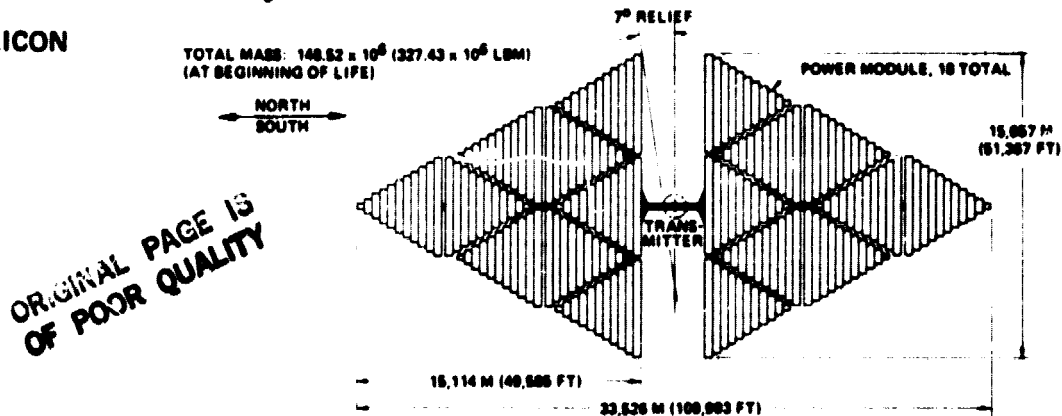
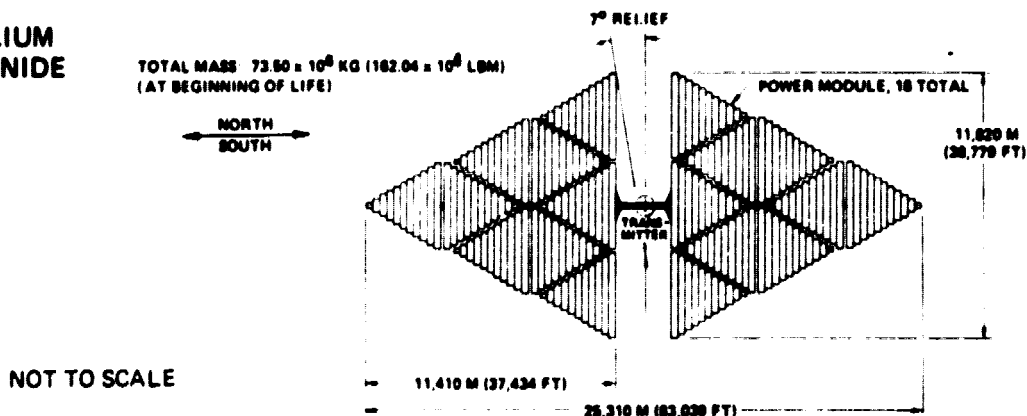
GALLIUM
ARSENIDE

Figure 4-1. Photovoltaic Satellite Configurations (End of Life)

Note that both satellites have 18 power generation modules. Modularity is employed to allow addition of cell area with time to compensate for cell degradation from radiation effects. Cell area addition was selected from several options for the compensation of degradation, as given in Table 4-1.

Table 4-1. Options to Counter Cell Degradation

Number	Option	Evaluation
1	Anneal Cells	Uncertain
2	Add entire satellites	Wastes microwave power transport
3	Initial oversize	Higher front end cost
4	Add modules	Costs distributed over program

Hence the silicon photovoltaic satellite begins its operational life with 12 modules installed; the ground output is 10 GW. Over a period of 30 years (the baselined SPS life) six other modules are added to yield the total of 18 shown in Figure 4-1. The higher radiation resistance of the gallium arsenide heterojunction cell allows that SPS to begin its life with 16 modules; only 2 are added.

As previously explained, the degradation rate of the silicon solar cell would be much higher if it were not for the presence of cover glasses and aluminum "cooling sheet" behind the cells. The cooling sheet is shown in Figure 4-2, along with the cells and the compound parabolic concentrators (CPC).

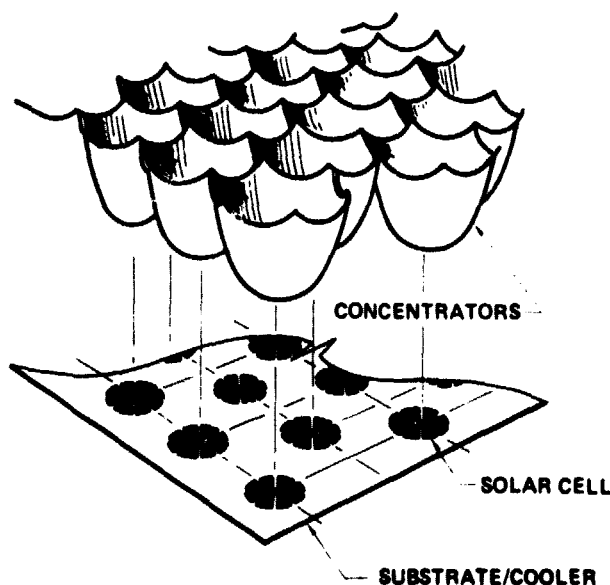


Figure 4-2. Cells, Coolers and Concentrators

The CPCs provide the required solar concentration (4.3 for silicon cells, 7.5 for gallium arsenide). Each cell is equipped with a CPC, roughly conical in form but with sides which are parabolic in cross section. Figure 4-3 shows the CPCs baselined, approximately 1/2 size.

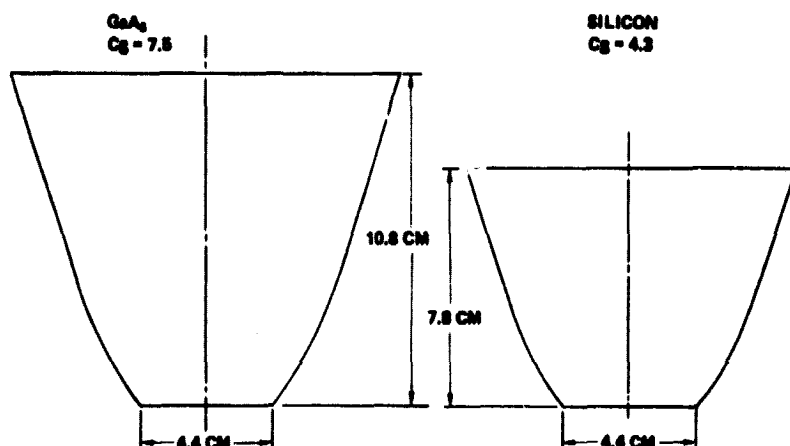


Figure 4-3. Compound Parabolic Concentrators (1/2 Scale)

The CPC's are formed of thin aluminum. They are added to the solar arrays in sheets approximately 1 meter (39.37 inches) square. The CPC can accept solar pointing errors of up to 12° with small (less than 3%) losses). They also block sunlight from the cooling sheet reducing its temperature. Solar arrays would be rolled or folded for transportation to orbit; the CPC's are added in orbit. Space fabrication of CPC's may be practical.

4.3 BRAYTON SATELLITE CONFIGURATION

Figure 4-4 shows the general arrangement of the Brayton (turbomachine) satellite. Four power generating modules are employed with a single transmitter.

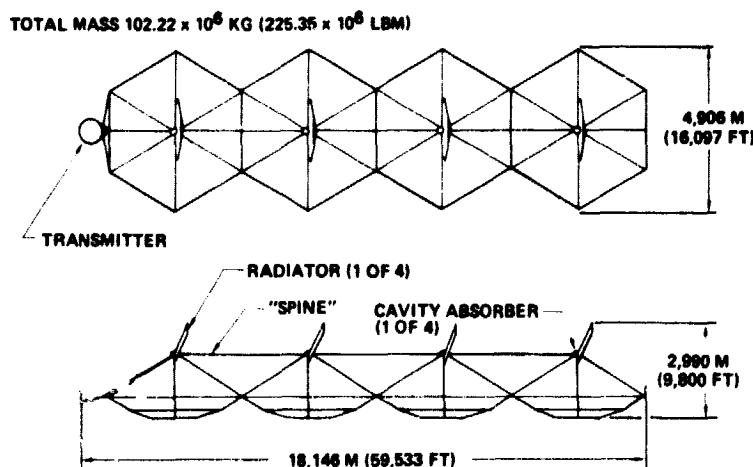


Figure 4-4. Brayton Satellite Configuration

Each power generating module is composed of a solar concentrator dish and a focal point assembly. The solar concentrator dish is made up of a supporting framework and 16,800 solar reflector facets (mirrors). Figure 4-5 shows the principle of the concentrator system.

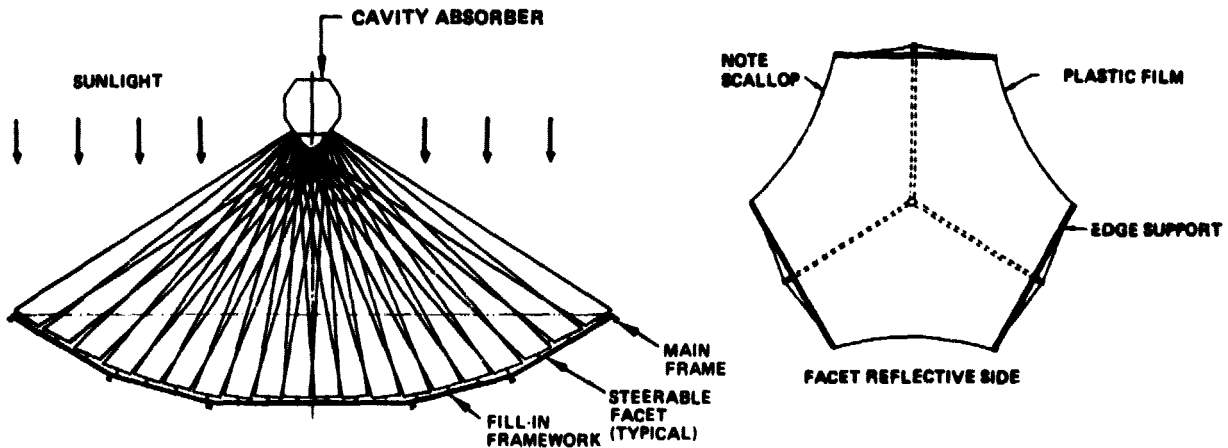


Figure 4-5. Solar Concentrator System

The reflector facets are formed of tensioned aluminized Kapton $8\mu\text{M}$ (1/3 mil) thick. Graphite-epoxy tubing forms the tensioning frame. Each facet is equipped with a sensor/servomechanism system which steers it through the small angle necessary to keep its reflected solar energy entering the aperture of the focal point assembly.

Figure 4-6 shows the focal point assembly.

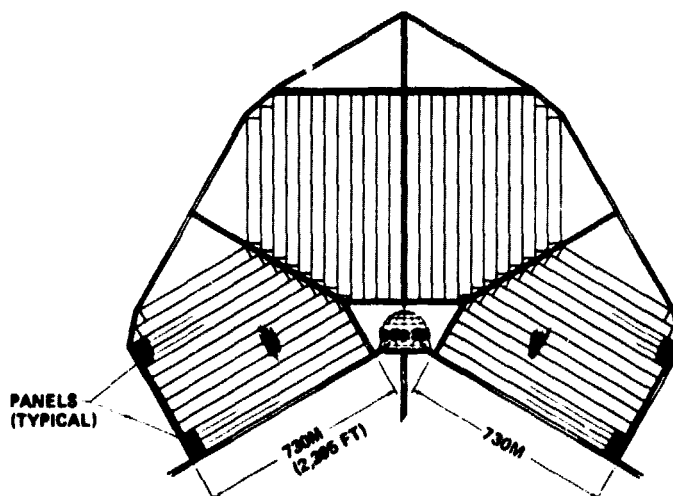


Figure 4-6. Focal Point Assembly

The radiator rejects waste heat from the Brayton cycle. The radiator is composed of panels of water heat pipes linked to the turbomachines by liquid metal (sodium/potassium - NaK) filled manifolds. The cavity absorber assembly is a hollow sphere formed of insulated panels. Around it are located 16 Brayton turbomachines, the generators of which each produce 300 MW of electric power. Heat exchanger sets to transfer solar energy to the helium-xenon working fluid line the interior walls of the cavity. The turbine inlet temperature is 1620K (2456°F). The efficiency of conversion of thermal energy to shaft power by the turbomachines is 45.4%.

4.4 THERMIONIC SATELLITE CONFIGURATION

Figure 4-7 shows the general arrangement of the thermionic SPS.

TOTAL MASS 196.48×10^6 KG = 433.1×10^6 LBM

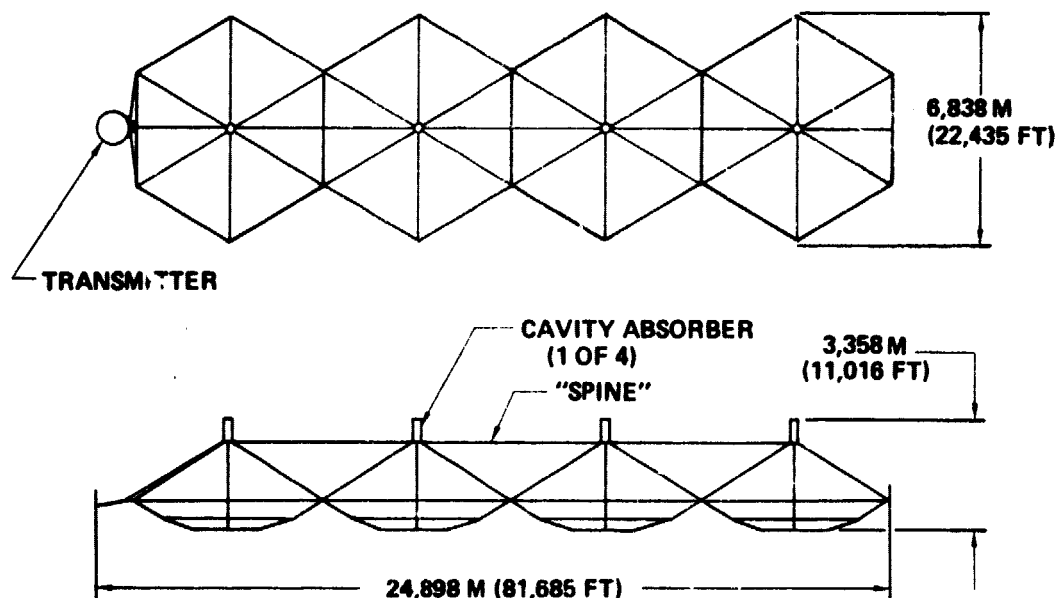


Figure 4-7. Thermionic Satellite Configuration

The four power generation modules employ individual steerable reflector facets similar to those used with the Brayton system; refer back to Figure 4-5. The cylindrical cavity absorber assemblies are lined with thermionic diode assemblies which convert the concentrated solar energy to direct current electricity.

Figure 4-8 is a cross section of a thermionic diode. Its molybdenum emitter is exposed to the interior of the cavity absorber and attains a temperature of 1800K (2780°F). Its molybdenum-coated nickel collector is attached to a sodium-filled nickel heat pipe which provides cooling to a temperature of 1000K (1340°F).

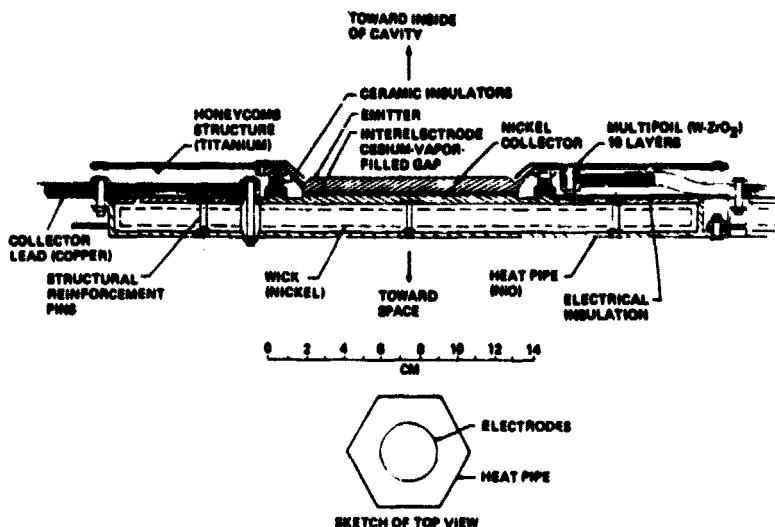


Figure 4-8. Thermionic Diode Cross Section

The hexagonal heat pipes are clustered into panels each 20 m (65.6 ft) square. Four of these panels are combined with a power convertor panel to form a cross-shaped group as shown in Figure 4-9. The power converters step up the low voltage direct current output of the diodes to high voltage alternating current for routing to the transmitter. The thermionic diodes convert thermal energy to direct current with an efficiency of 24%.

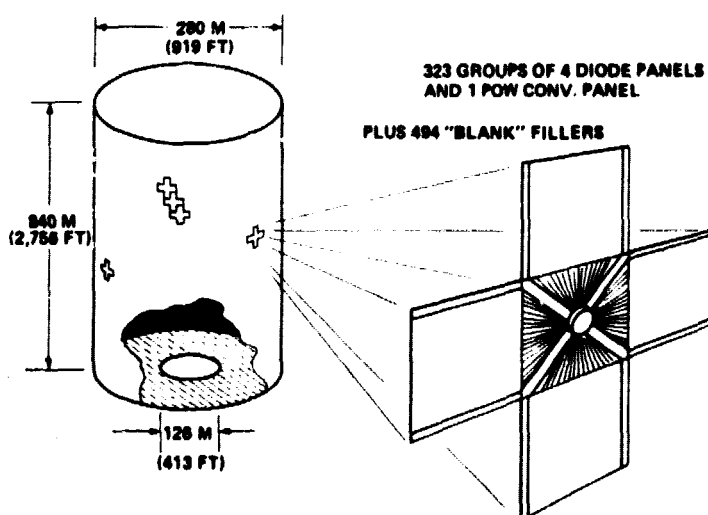
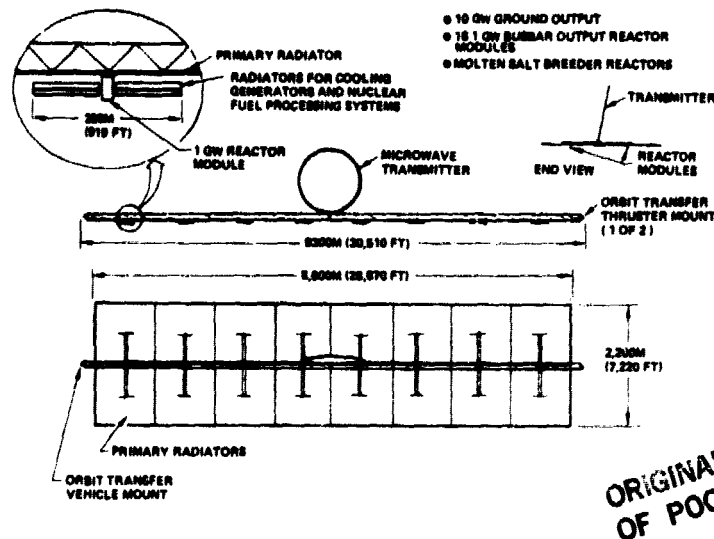


Figure 4-9. Diode and Power Conversion Panel Group

4.5 NUCLEAR SATELLITE CONFIGURATIONS

Breeder reactors were baselined for this study due to the generally low forecasts for nuclear fuel availability by the 2000 to 2020 time period. A large number of candidate breeder reactor types were evaluated. The one judged most likely to be successfully developed in the required time period was the molten salt breeder reactor (MSBR). Figure 4-10 shows a 10 GW ground output MSBR satellite,



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OF POOR QUALITY

Figure 4-10. MSBR Nuclear Satellite

Note that the surface area of the unit consists of the radiator system required to cool the Brayton systems. 16 power pods are employed; each pod has a reactor and four 300 MW turbomachines. Figure 4-11 is a cutaway of a power pod.

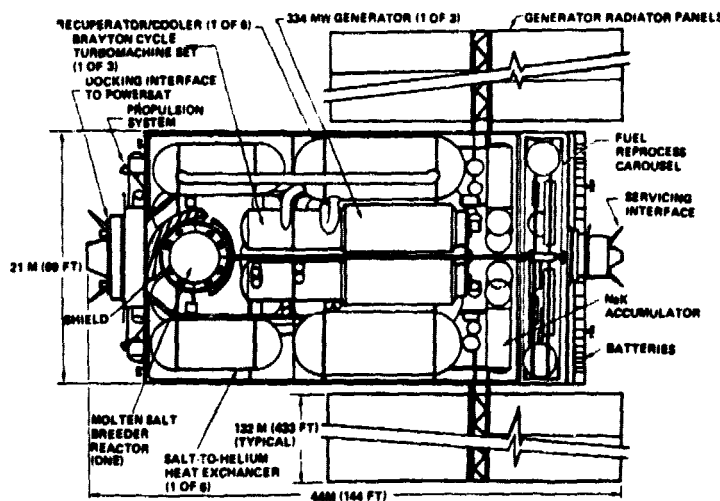


Figure 4-11. MSBR Power Pod

Each power pod incorporates a shield located between the reactor and the transmitter electronics. For major maintenance, a power pod can be undocked and flown some distance away from the basic SPS. After the pod's reactor has been shut down for a few days, it may be approached for maintenance. Thus it is not necessary to shut down an entire SPS to service one reactor.

The molten salt is continuously circulated through a fuel reprocessing system which adds fertile nuclear fuel, removes bred fuel and wastes and adjusts the salt mixture to suit reactivity requirements. Nuclear wastes are either kept at the satellite or rocketed out of the solar system; geosynchronous orbit altitude and velocity would facilitate this operation.

Chemical effects from compounds which are produced in the molten salt limit the reactor outlet temperature to 1030K (1395°F) for a useful life of 30 years. This is a far lower temperature than achievable with the solar Brayton system, wherein only chemically inert materials (helium-xenon) contact the heat exchanger tubing. The lower turbine inlet temperature means lower turbomachine efficiency; this results in the nuclear MSBR being more than twice as massive as the solar Brayton SPS.

Other reactor types investigated had similar heat exchanger material problems; for example free fluorine in the uranium hexafluoride (UF_6) reactor limited heat exchanger temperature to about 900K (1160°F). Near the end of the study attention was consequently turned to a reactor type which does not employ a conventional heat exchanger to heat the helium-xenon working fluid. Such a reactor is the rotating particle bed reactor (RPBR); two potential ways of implementing such a reactor are shown in Figure 4-12.

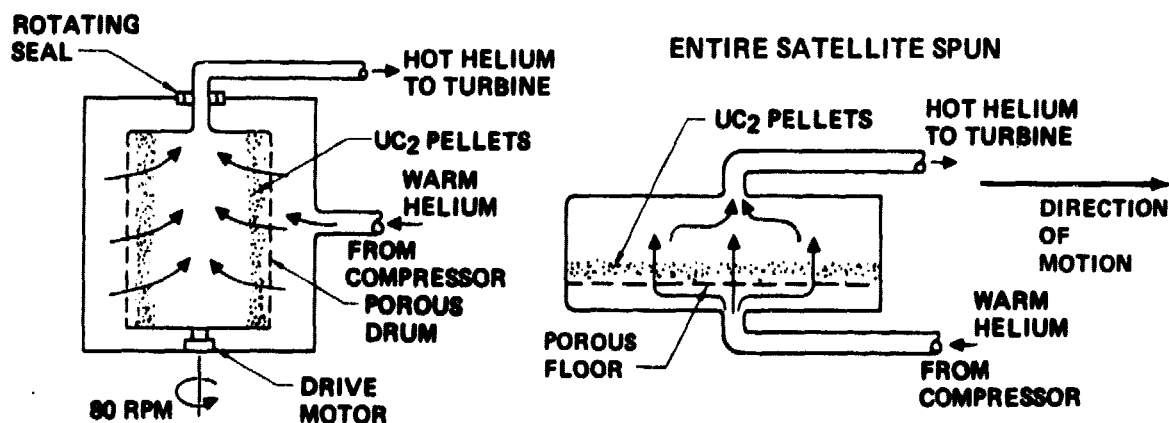


Figure 4-12. Rotating Particle Bed Reactor Concepts

Both concepts employ centrifugal force to hold the reactor fuel pellets in place; the helium-xenon flow levitates the particles away from the walls. Heat is transferred to the gas as it passes between the pellets. Absence of heat exchanger tubing and small pellet diameters may permit gas temperatures as high as in the solar system (1620K (2456°F) or even up to 2000K (3140°F). This might lead to a nuclear SPS as light as or even lighter than the solar SPS. However, the RPBR breeder reactor must be considered a rather advanced development.

4.6 COMPARISON OF SPS CONCEPTS

Figure 4-13 shows the SPS concepts to the same scale.

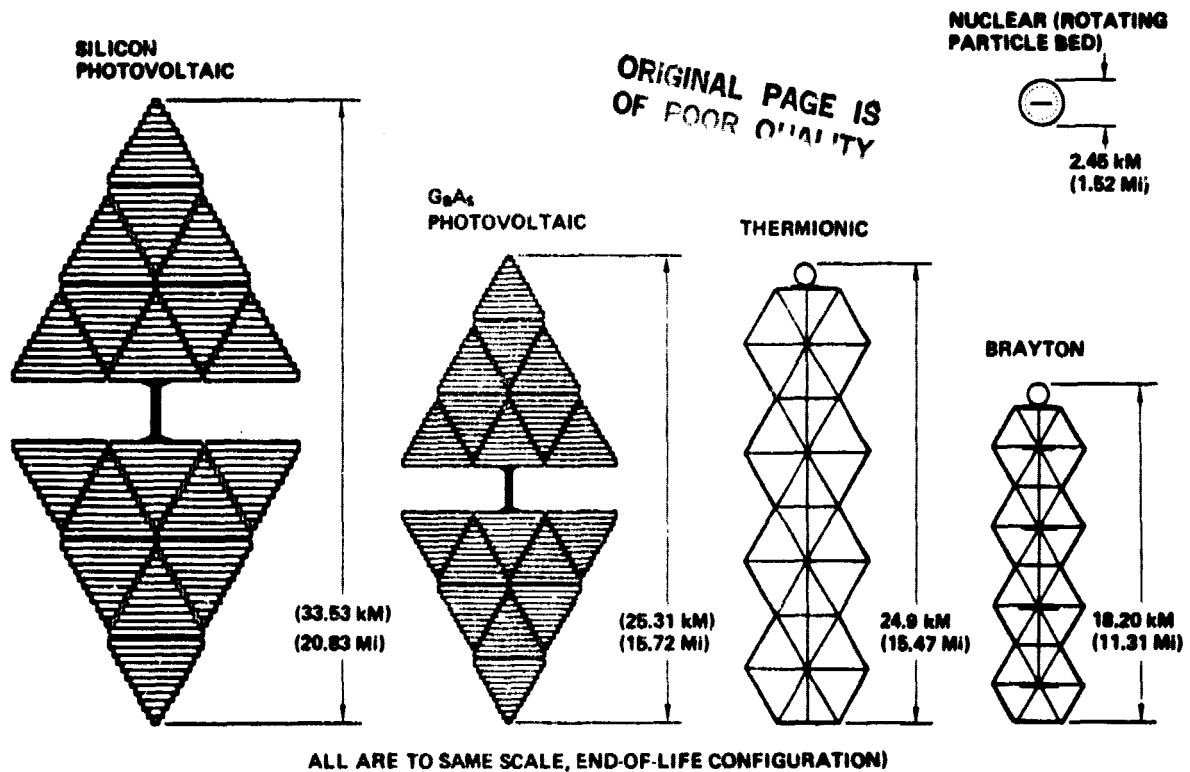


Figure 4-13. SPS Concepts to Scale (10 GW Ground Output)

The photovoltaic satellites are shown in end-of-life configuration; 18 modules are installed on each. As previously explained, the silicon SPS begins life with 12 modules producing a full output; to counter solar cell degradation six additional modules are installed during the 30 year life. The gallium arsenide satellite starts with 16 modules; two are subsequently installed. The size differential between the SPS concepts results from the basic energy conversion efficiencies of each.

Figure 4-14 shows the masses of each satellite type at beginning-of-life (BOL) and end-of-life (EOL). The mass increase for the photovoltaic satellites results from the addition of cell area to counter degradation. In the solar Brayton system pressure-induced creep growth of the radiator manifolds requires that fluid be added over the 30 year life, resulting in the mass change shown.

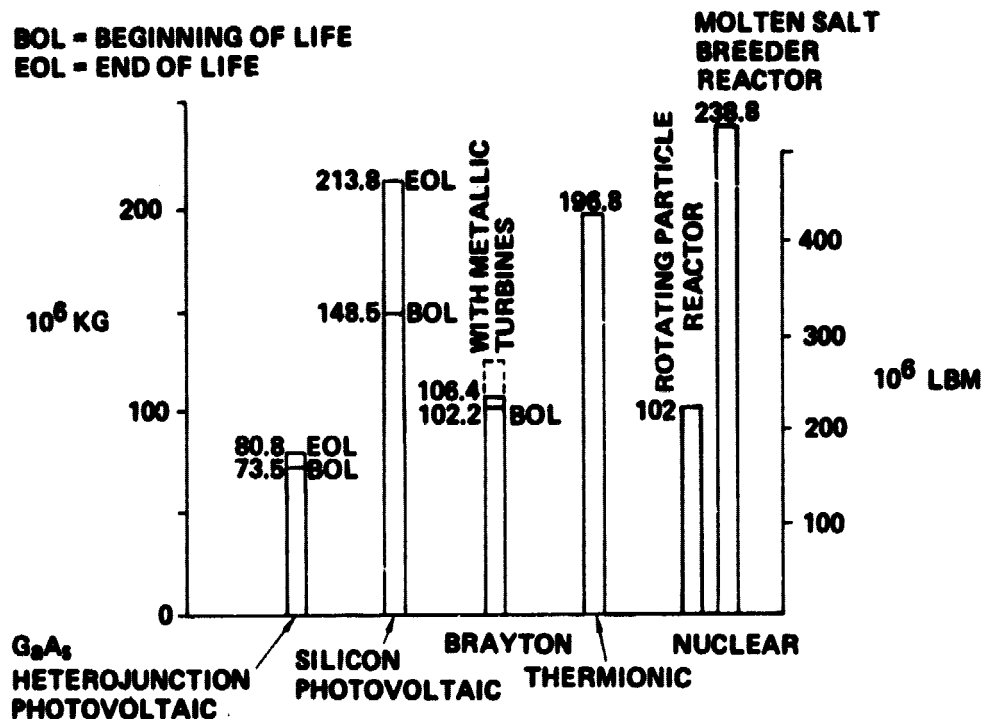


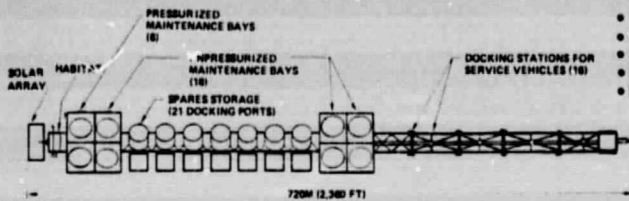
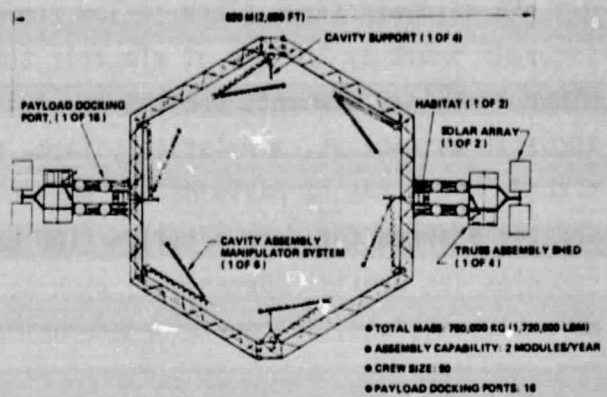
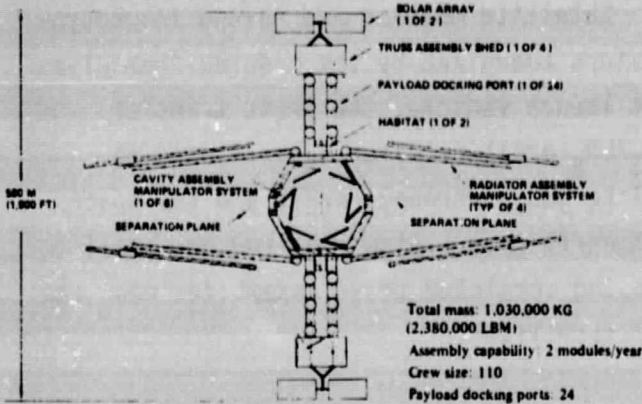
Figure 4-14. Comparison of Satellite Masses

Two nuclear SPS types are shown in Figure 4-14; the molten salt breeder reactor SPS and the somewhat more advanced concept, the rotating particle bed (RPBR) SPS.

Approximately 25% of the mass of the thermionic SPS is represented by the interelectrode busses between the diodes. Rearrangement of the heat pipe shape might be used to bring the diodes closer together, allowing shorter interelectrode busses and a significant mass reduction.

4.7 AUXILIARY SYSTEMS

Figure 4-15 shows assembly and support stations as configured for each SPS concept and for the microwave transmitter which is common to each.



- Total mass (without spares or support vehicles): 600,000 KG
- Support capability: up to Powersats producing a total of 100 GW ground output
- Payload docking ports: 21
- Maximum crew size: 50
- Placement: by arriving Powersat module

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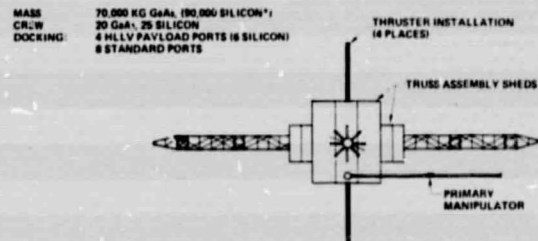
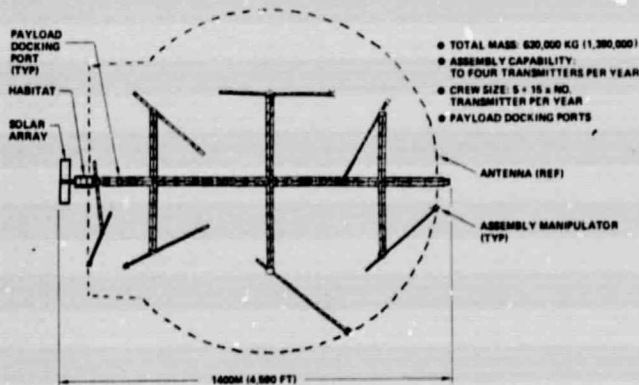
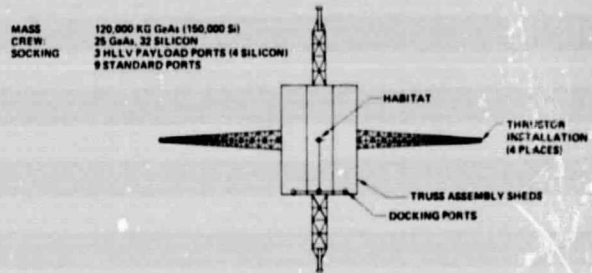
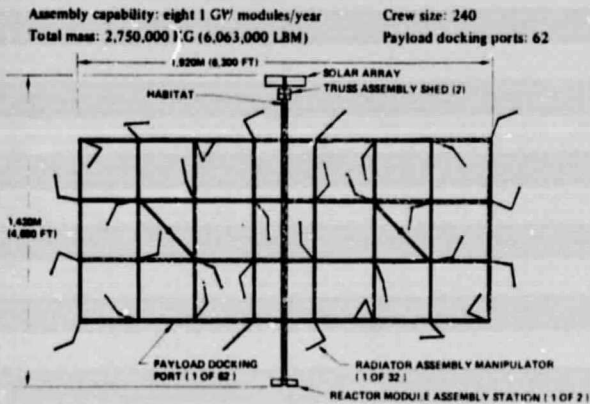


Figure 4-15. Assembly and Support Stations (Not to Scale)

All SPS assembly takes place in low orbit. Satellite modules are raised to geosynchronous orbit by the use of electric thrusters energized by the modules themselves. Other auxiliary elements are the heavy lift launch vehicle, the orbit transfer thruster assemblies, a relatively large LH_2/LO_2 orbit transfer vehicle used to transfer maintenance payloads and personnel to geosynchronous orbit and the space shuttle adapted for crew rotation (100 persons/flight). Also required are small vehicles for orbital operations, such as moving completed truss assemblies near the assembly stations, or servicing operational satellites.

5.0 PROGRAMS

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5.1 OPERATIONAL PROGRAM

Each power satellite type was required to produce the first large scale power from space in 1996. Ten years later 10% of our national electrical power needs were to be filled by SPS; in 20 years, 25%. This set the required "make operable" rate and the total power to be produced. The ultimate SPS generating capacity required is 600 GW, in the year 2016. Each satellite has a 30 year useful life.

For each satellite type a total program was defined as given in Figure 5-1 (example shown is for the silicon photovoltaic SPS).

	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
SPS ADDED EACH YEAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
TOTAL SPS AVAILABLE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
RECTENNAS ADDED	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
TOTAL RECTENNAS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
GROUND OUTPUT GW ADDED	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
GROUND OUTPUT GW AVAILABLE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
NUMBER OF MAKE UP MODULES ADDED	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
LOW ORBIT STATIONS IN OPERATION (FRAME)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
TRANSMITTER STATIONS IN OP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
GSO STATIONS IN OP (MODULE STA)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
PERSONNEL IN LOW ORBIT	77	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182
PERSONNEL IN HIGH ORBIT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
HEAVY LIFT LAUNCHES PER YEAR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
MODULES TRANSFERRED TO HIGH ORBIT (BASIC)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
GSO FREIGHTER TRIPS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
SUPPORTING SHUTTLE LAUNCHES (G.OWTH)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
HEAVY LIFT VEHICLES PROCURED W/O WEAROUT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
GSO FREIGHTERS PROCURED W/O WEAROUT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
MODULE TRANSFER SETS PROCURED	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
MODULE ASSEMBLY STATIONS (LEO)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

(NOT INCLUDING WEAROUT)

(NOT INCLUDING WEAROUT)

Figure 5-1. Typical Program Definition

All major program elements are identified and quantities for each are given. Of interest in this example program is the placement rate for the "make-up modules" which counter cell degradation. Programs for other SPS options are given in the companion volume "Detailed Technical Report".

5.1 PRECURSOR PROGRAM

A precursor program was baselined which incorporates:

- o Ground testing and analysis
- o Development test shuttle sortie flights
- o A "pilot plant"

The pilot plant is a subscale SPS unit which serves to demonstrate, in an integrated fashion, all major features of the SPS.

A pilot plant was baselined for two reasons: first, analysis of critical SPS factors indicated that long term (i.e., one year or more) successful pointing from geosynchronous orbit of a microwave beam carrying significant (i.e., detectable when added to power grid) power would most probably be required. This can best be accomplished by a geosynchronous pilot plant. Secondly, analysis of recent energy programs (e.g., conventional power reactors) and energy programs currently studied by ERDA (ground solar power, liquid metal fast breeder reactor and fusion) indicates a common element, a pilot plant.

Figure 5-2 shows an example pilot plant. It and its associated assembly station could be launched in two years with two space shuttles with a two-week turnaround time. The assembly station moves to geosynchronous orbit with the pilot plant and becomes the service base there during the test period.

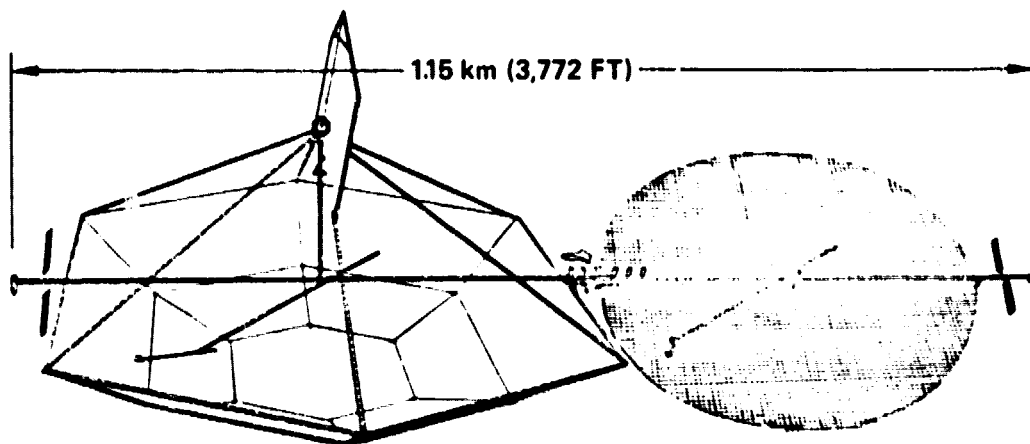


Figure 5-2. Example Pilot Plant

This pilot plant would transmit a microwave beam which would fit within a government reservation such as White Sands Proving Grounds. The microwave beam strength would be extremely low, yet over one megawatt of power could be produced by the test receiving antenna.

6.0 COSTS

Each SPS program element was costed, using as a basis the program definitions (see example in Figure 5-1). Cost data for transportation elements was drawn from concurrent studies. Other program elements were costed in estimating relationships more fully defined in the companion volume "Detailed Technical Report".

Figure 6-1 gives total life cycle costs, i.e. program costs divided by the number of satellites, for each SPS type. Program costs include development, facilitization (including assembly stations), the satellites themselves, all launches, maintenance, etc. Not included are taxes, depreciation and profit.

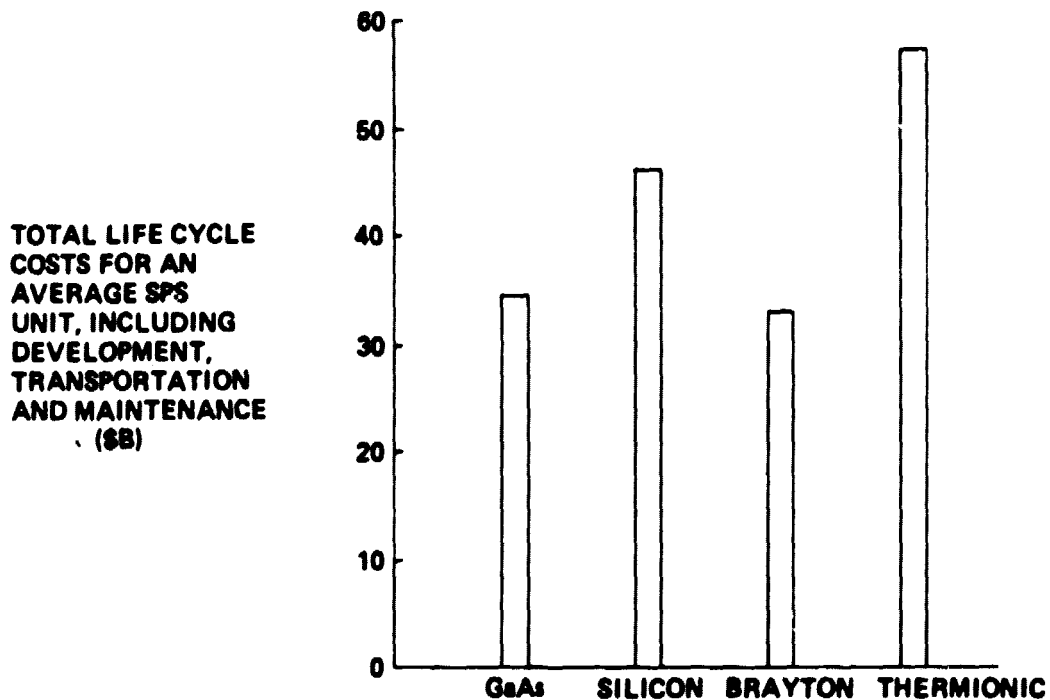


Figure 6--1. SPS Life Cycle Costs

All SPS options produce the same electric power. A 7.5% discount rate was used to determine the required busbar cost (at the ground rectenna output) to amortize the program costs given above. These required busbar costs are given in Figure 6-2.

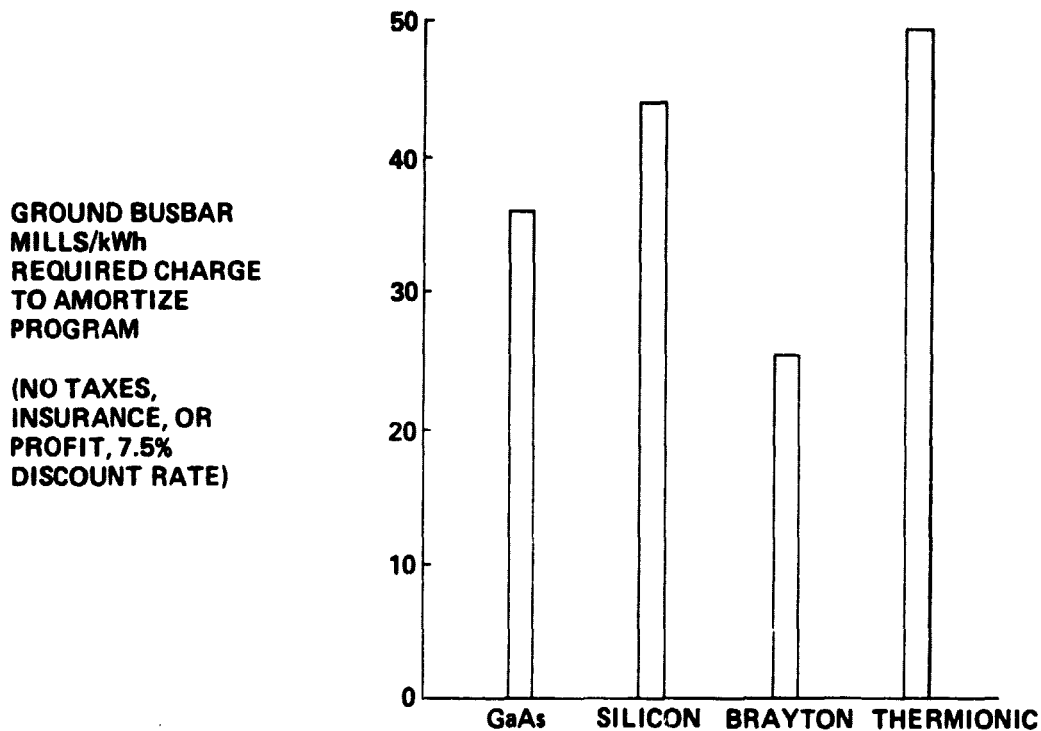


Figure 6-2. Required Busbar Power Costs

Power costs for the nuclear MSBR concept were estimated at 82 mills/kWh. The more advanced rotating particle bed reactor concept conceivably could provide costs in the 25 to 45 mills/kWh range.

7.0 OVERVIEW

As explained in Section 3.1, several concepts were de-emphasized for a variety of technical reasons. However, the net result of this study is that "power from space" is not dependent upon a single power generation concept. Analyses of the exhaust emission quantities of the associated launch systems, rectenna land use, etc. indicate that the environmental impact associated with the SPS concept is extremely low.

The baseline program would produce the first commercial power from space in 1996. This would be by no means an "accelerated" program; SPS operation could probably be achieved at a much earlier date.